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EXPERIMENTS WITH CHOIRS – PRACTICE AND PITFALLS

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1 INTRODUCTION

This paper presents work in progress undertaken with choirs in their normal rehearsal venues to discover why they do not maintain pitch regularly when singing a *cappella* music.

Following an extensive survey of choral practitioners which gathered evidence of pitch drift in a *cappella* choral singing, a series of experiments has been undertaken with amateur choirs around the United Kingdom. For each choir, data was collected over twenty rehearsals by a member of the choir using equipment supplied by the Open University. The data collected includes recordings of a specially composed work, acoustic and environmental measurements, singers' attendance and a summary of each rehearsal by the conductor. In addition, singers were asked to take part in a listening test which measured their ability to discriminate pitch differences between two notes.

In this paper, the method of assessing any pitch variation in the recordings from each choir will be demonstrated and initial findings reviewed. A discussion of the results from the listening test survey, taken by individual singers from each choir, will be presented. Finally, a comparison of the choirs and their rehearsal venues will be undertaken along with examples of the problems experienced with individual choirs during the experiments.

2 BACKGROUND TO THE PROJECT

When singing unaccompanied music, choirs do not always maintain pitch. Terasawa¹ describes the problems of pitch drift encountered by a university choir when singing Bruckner's *Os Justi*, stating that the music is seen as the cause of the choir losing a semitone each time it is sung. The effect of the music on pitch maintenance is supported by Howard² who sees a direct relationship between certain intervals within the music and the loss of pitch. Schoenberg³ writes that choirs can drift in pitch because natural semitones, (i.e. just intonation), differ in size from those of equal temperament. Indeed he advises singers to be trained to the intervals of the tempered scale to assure correct musical intonation. Edwards⁴ finds that, in his experience, most unaccompanied music written in certain keys, including F major and A minor, will "almost automatically" lose pitch. Rutter⁵ supports this, stating that the nature of choral writing influences the propensity of choirs to drift in pitch.

However, if the intrinsic features of a piece of music (for example its harmonic structure) were the sole cause of this phenomenon, then why do choirs apparently maintain pitch on some occasions but not on others when performing the same piece of music? Speak to anyone involved with choral singing and they will support this notion. Potter⁶ states that pitch can be affected by all sorts of extraneous factors including, as examples, the weather, central heating and humidity. This is reinforced by Halsey⁷ who tells of sinking down a semitone "...on snowy Fridays when everyone was tired.". Potter does go on to say that performers should not overly worry about pitch as the overall performance may be more acceptable, and the audience more settled, by staying in the pitch to which the performers have slipped. Here is evidence, albeit anecdotal, of physical conditions affecting pitch and also that the pitch has

gone down. Potter and Halsey agree that finding a more suitable initial pitch may lead to a more stable performance.

This current research is exploring possible causes, other than those of the music itself, that may contribute to pitch drift in a *cappella* Western choral singing.

3 EXPERIMENTS WITH CHOIRS

3.1 Introduction

A literature search was undertaken to discover the extent of research into choral intonation and pitch drift. The terms 'intonation' and 'pitch drift' are both used when discussing problems of keeping in tune. Latham⁸ describes intonation as being used to indicate the state of a performer's tuning; it being possible to decide between 'good' and 'poor' intonation. Howard⁹ used an electrolaryngograph connected to each of four singers, along with four separate microphones, to study pitch drift. Ternström and Sundberg¹⁰ provided headphones and seated singers in front of a microphone situated in an anechoic chamber to investigate intonation precision. Jers and Ternström¹¹ used individual microphones with 16 singers to analyze intonation in multichannel recording. In all these examples, the tests were undertaken in laboratories taking the singers out of their normal performance environment, be it a rehearsal room or concert hall. Given that the current project is focused on researching why pitch drifts when choirs sing unaccompanied music, it was decided that experiments should be performed in the choir's regular singing environment and with the type of music they would normally sing. Singers were expected to treat the experiments as part of their normal rehearsal with as little awareness as possible that recordings were being made. Rehearsals were chosen instead of concerts for the experiments as most amateur choirs only take part in concerts a few times a year and insufficient data would be collected to give significance to the results.

The experiments were designed to be around five minutes in length to avoid disruption to valuable rehearsal time. Most amateur choirs only rehearse once a week, so taking even these few minutes out of a tight rehearsal schedule could jeopardize a concert performance. The project team is therefore indebted to the eleven choirs who finally agreed to take part in the experiments.

A range of choirs were recruited as shown in Table 1. Singers' skill levels varied from fully professional to fully amateur, and their ages from seven years old to over eighty years old. All choirs were mixed gender apart from the two barbershop choruses which were both all male.

Choir	Choir type	Number of singers	Audition?
A	Chamber	26	No
B	Church	12	No
C	Chamber	20	Yes
D	Barbershop	25	Yes
E	Chamber	30	Yes
F	Chamber	25	No
G	Choral Society	65	No
H	Chamber	20	No
I	Chamber	9	Yes
J	Chamber	22	Yes
K	Barbershop	25	Yes

Table 1 Details of choirs

The choirs were situated around the UK, as shown in Figure 1. Also included is the location of the National Physical Laboratory (NPL) which collects atmospheric pressure readings subsequently used in the experiments.

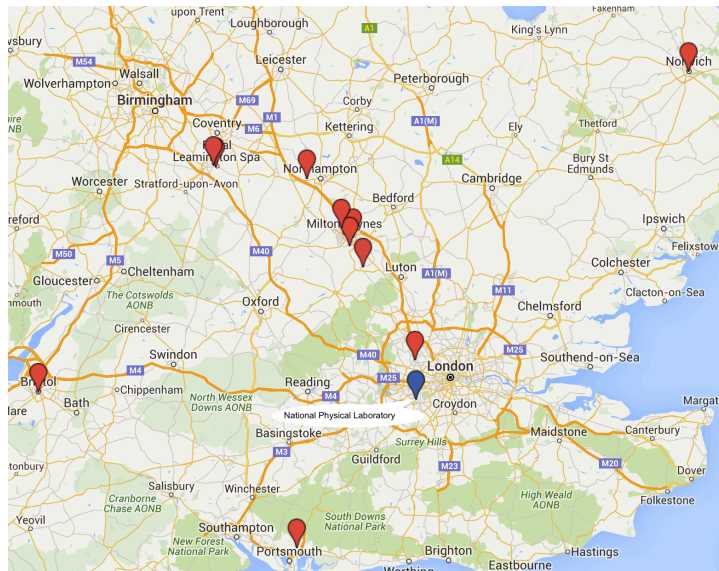


Figure 1 Distribution of choirs (red markers) and location of the National Physical Laboratory (blue marker)

It was not feasible to visit each choir regularly to undertake the experiments, so the choirs needed to implement the experiments and collect the data themselves. The Open University's Experience of in providing *Home Experiment Kits* enabled a suitable experiment kit to be devised, delivered and supported by the project team.

In addition, individual singers in each choir were encouraged to complete a listening test to establish their pitch discrimination. Measurements of the acoustic properties of each of the rehearsal venues were made when a member of the project team met with the different choirs to introduce the project and deliver the experiment kit.

3.2 Experiment kit

The experiment kit comprised a small portable audio recorder, an environmental meter (capable of measuring temperature, humidity, light and sound levels), connection leads, spare batteries and instructions. Forms were provided for the person taking the recording and measurements, and a questionnaire given to the conductor, to complete after each rehearsal. Arrangements were made for collection of the attendance data which had to be suitably anonymised.

3.2.1 Audio recordings

A *Sony IDC-PX333 IC Recorder* was chosen for making the recordings. Although primarily a speech recorder, it has several recording modes including a high quality one with a frequency response of 75 Hz to 20 kHz, adequate for the analysis of singing. Files are stored in *MPEG-2 Audio Layer III* (MP3) format with a selected sample rate of 44.1 kHz and a compressed bit rate of 192 kbps. Equally important is its ease of use, with a single button for starting and stopping recording. The recorder can be configured for a range of settings from dictation, where the microphone is close to the mouth, to lectures where a wide range of sounds may be employed. This setting was chosen for recording choirs. The microphone sensitivity can also be altered; in most cases low sensitivity was chosen, but this was checked when the experiment kit was delivered. Although the recorder has 4 GB of internal memory, an additional 8 GB *microSD* card was fitted giving 90 hours of recording time without recourse to the internal memory, sufficient for 20 four-hour rehearsals!

All choirs were asked to make recordings at each of twenty rehearsals. For each choir, the same venue was to be used at each rehearsal and two songs were to be performed. The first

was *Test Piece* written by Dr Dennis Pim especially for the project. The piece is designed to practise the choir's production of vowel sounds, and its text consists entirely of syllables such as "la", "te" and "doo". It can be sung in under two minutes. The second song could be chosen by the choir, although they were encouraged to sing *Heraclitus* by Stanford. Unfortunately, this part-song was not seen as suitable or appropriate by several choirs leading to a range of songs being used, from the 16th century's *Ego Sum Panis Vivus* by Palestrina to the 20th century's *Can you feel the love tonight?* by John and Rice, taken from the Disney animated film, *The Lion King*.

The reason for suggesting *Heraclitus* relates to the work of Professor David Howard¹², who hypothesizes that the likelihood of the occurrence of pitch drift can be calculated from the intrinsic properties of a piece of music. *Heraclitus* was listed by Howard as a piece he had tested and found to be neutral, and Pim's *Test Piece* was also found to be neutral in Howard's test, as shown in Figure 2. To apply this test, each note and chord is entered in a spreadsheet and the probability of the next note moving away from the equal temperament scale through singers' natural propensity to use exact harmonic tuning is tested and a value assigned. This makes it possible to determine whether the composition is neutral or has an overall tendency to drift either sharp or flat. Figure 2 demonstrates that whilst individual notes in the four parts may sharpen or flatten, the final chord should be within 15 cents (a cent being 100th of a semitone). which is virtually indistinguishable to the average ear and making this piece neutral. This eliminates the possibility that drift is due to the music.

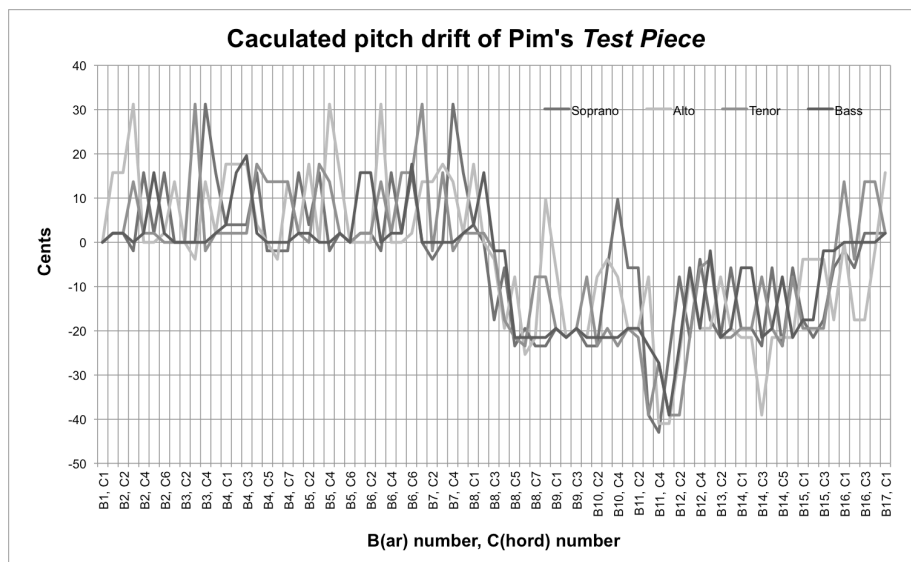


Figure 2 Howard's test results for Pim's *Test Piece* show it to be neutral overall

3.2.2 Environment measurements

A *Maplin 4-in-1 Multi-Function Environment Meter N09AQ* was selected for environmental measurements. This is capable of measuring temperature, humidity, light and sound levels. A carry-case was included with this meter, which conveniently was large enough to contain all the other equipment in the experiment kit too. For each choir, temperature and humidity were measured at the same time as each audio recording. The meter has no data storage facility and so measurements had to be transferred to a chart. Initially measurements of the light level and background noise were also made at each rehearsal, but a pilot experiment showed that these levels generally tended to stay reasonably constant, and it proved unnecessary for them to be made weekly. If changes were observed, (e.g. a change from artificial to natural light), then choirs were asked to take additional measurements. Atmospheric pressure was not measured at the rehearsal sites as the cost of including a suitable digital barometer in each experiment kit was outside the allocated budget. Instead atmospheric pressure readings from the National Physical Laboratory (NPL)¹⁰ are being used. NPL provide accurate measurements of the pressure every ten minutes and also provide historical data. The NPL is

situated to the west of London, as shown in Figure 1, and is centrally situated to all the choir locations. It is the effect of a possible change in pressure on pitch drift at each rehearsal that is being studied, so a country-wide value will suffice.

3.2.3 Rehearsal questionnaire and attendance

At each rehearsal the conductor was asked to complete a short questionnaire, giving an opinion on the performance and an estimation of how well the choir maintained pitch. For each of these two questions, a simple scale from A (excellent) to E (poor) was used along with brief comments. Conductors were also asked whether any key singers had not attended the rehearsal. Anonymised attendance registers were also required to support the conductor's responses.

3.3 Pitch Discrimination

Work on pitch discrimination was originally undertaken by Seashore¹³ who established that the average person is able to discriminate between two tones when they are 12 or more cents apart.

3.3.1 Listening test

A listening test using tone pairs based on Seashore's work was developed. In total 22 pairs of sine waves, with pitch differences ranging between ± 47 cents, and including four pairs where they were equal, were played in a random order to individuals taking the test. The first tone was always A4 (440Hz).

Pitch perception is logarithmic so intervals arise from equal frequency ratios rather than equal frequency steps. This leads to a scale where the pitch doubles for each octave. Thus given that the frequency of A4 is 440Hz then that of A3, the octave below, is 220 Hz and that of A5, the octave above, is 880Hz. The octave is subdivided equally into 12 semitones and each semitone is further divided into 100 cents giving a total of 1200 cents to the octave. Given that the frequency ratio of the octave is 2:1, then the ratio of each equal-tempered semitone will be the number which, when multiplied by itself twelve times, doubles the frequency. Mathematically, this gives the frequency ratio of the equal-tempered semitone as the twelfth root of 2 (equation 1).

$$\text{Frequency ratio for an equal-tempered semitone} = 2^{\sqrt[12]} \approx 1.0595 \quad (1)$$

Further subdividing each semitone into 100 cents gives a frequency ratio for each equal-tempered cent as the 1200th root of 2 (equation 2).

$$\text{Frequency ratio for an equal-tempered cent} = 2^{\sqrt[1200]} \approx 1.000578 \quad (2)$$

The frequency of each semitone was calculated in a *Microsoft Excel* spreadsheet by starting at A₃ (220Hz) and repeatedly multiplying the previous semitone by the formula $\text{POWER}(2,1/12)$. Meanwhile, the frequency of each cent in the semitone was calculated by multiplying the previous value by $\text{POWER}(2,1/1200)$

Matlab R2014a, from *The Mathworks Inc.*, was used to generate each tone from the calculated frequencies using a library program, with the tones generated in wav format. The required frequency was entered into the program along with the length of the sound in seconds, the bits per sample and the sample rate. The tone pairs, with the first tone set to A4 (440Hz) and the second ranging between ± 47 cents as shown in Table 2, were edited using *Adobe Audition 6*.

	Frequency (Hz)	Variation (Cents)		Frequency (Hz)	Variation (Cents)
1	428.2154524	-47	10	440.254227	1
2	432.1913477	-31	11	440.508602	2
3	434.946169	-20	12	441.017791	4
4	435.952269	-16	13	442.037937	8
5	436.960698	-12	14	443.060442	12
6	437.971459	-8	15	444.085313	16
7	438.984558	-4	16	445.112554	20
8	439.491986	-2	17	447.949736	31
9	439.745919	-1	18	452.108860	47

Table 2 Tones with their frequencies and cent offset values based on A₄ (440Hz)

Each tone was modified by adding a fade-in and fade-out. For each tone pair, a quarter of a second silence was then inserted between the tones and also prior to the first tone and after the second tone as shown in Figure 3. Each pair was checked using *Audition's* frequency analysis application and was named with a random code so as not to give any hint as to the content and saved both as MP3 and wav files.

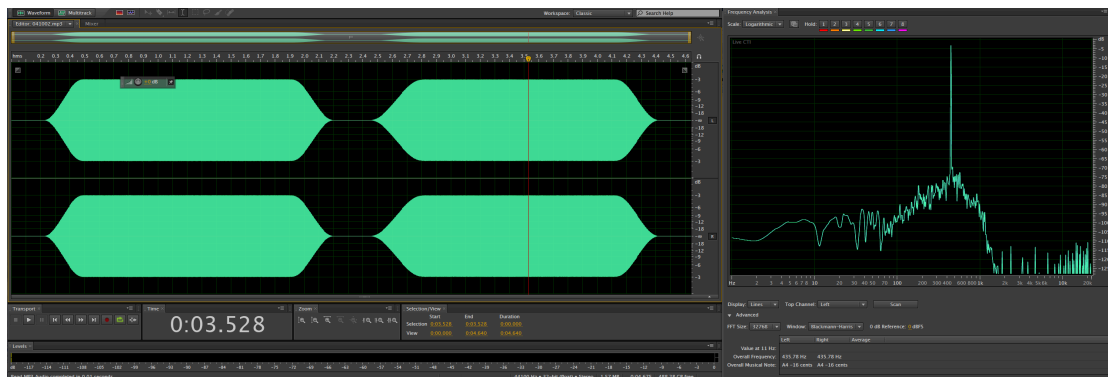


Figure 3 Tones were edited and checked for frequency using *Adobe Audition 6*

The listening test was built using *Surveygizmo's* web-based survey platform. This was chosen for its ability to support embedded audio files. A pilot listening test was built and tested with ten colleagues from the Open University's Faculty of Science, Technology, Engineering and Mathematics. Individuals took the test at the Milton Keynes campus using an *Apple iMac* computer with a pair of *Sennheiser HD 380 Pro* headphones. They then repeated the test on their own internet connected device (computer, smartphone or tablet), using their usual method of listening, and the results were compared. No significant changes were identified, giving assurance that the test could be run from any internet connected device without compromising the results. The order of the tones is randomized each time a test is taken so that individuals cannot compare results or learn the order. The test may be taken many times, although in practice this has not been the case. Initially the test was run using wav files but some delays in downloading were reported away from the campus and so it was decided to use smaller MP3 files with choirs. Multiple tests comparing wav and MP3 files did not demonstrate any significant differences in the responses, but download times were appreciably reduced.

Tests were tailored to each choir and password protected so that only singers from that choir could take part. An introductory letter giving details about the test was given to each singer. No personal data was recorded apart from the section of the choir in which the respondent sang.

3.4 Rehearsal Venues

The acoustical properties of each rehearsal venue were measured by a member of the project team. Initial measurements with one choir revealed that the presence of singers can significantly change the acoustic environment and so measurements were made with the choir in situ. Consequently it was important to ensure that the acoustic testing caused as little disruption as possible at the rehearsals. Measurements undertaken in the anechoic chamber at the Open University's campus at Milton Keynes showed insignificant differences in the results between exciting the chamber's acoustic properties with an audio sweep from an omnidirectional speaker and a balloon burst. Given the latter was far more convenient for use with choirs it was adopted for all the acoustic measurements. In practice, apart from a very few singers who were uncomfortable with loud noises leaving the rehearsal space before the test, this method caused little disruption to the rehearsal and even caused some amusement!

3.4.1 Acoustic measurements

Two balloons were burst in each venue from a position behind the singers (who were given a countdown to avoid any surprises). Singers were asked to keep quiet before and for at least 5 seconds after the balloon bursts. Recordings of the event were made using a single Behringer ECM8000 omnidirectional measurement condenser microphone placed on an extended stand at the position from which the conductor normally leads the choir. A Tascam CR-44WL digital audio recorder was set to make single channel recordings (in 16 bit wav format with a 48kHz sample rate, which is required by the acoustic analysis application). The Tascam recorder supports phantom powered microphones such as the ECM8000 and has the advantage of a dual recording mode whereby a second track is recorded 12dB below the manually set level. This provided a safety margin in case the main recording overloaded. No automatic gain control or limiting was used on the recordings. The recordings were edited using Audition with each balloon burst being identified from the original recording, copied and edited to 2.5 seconds in length, normalised to -1 dB and saved in the original format. They were transferred to the IR Room Impulse Response (IR) application which is part of the Studio Six Digital AudioTools suite running on an Apple iPad Air 2. The IR app calculates the most common acoustic metrics from the measured impulse response including ECT, RT60 and C80.

4 RESULTS

4.1 Choir experiments

To date four choirs have completed a full set of experiments with the remainder expecting to complete by the end of the year. Work has started on analyzing the results but so far only the data for one choir has been considered.

4.1.1 Recordings and measurements

The data analysis process is as follows. The weekly MP3 recordings for each choir are copied from the recorder and *Test Piece* and the song are copied and saved as mono wav files. Specific notes in each of these files are analyzed using *Melodyne Studio 4* from *Celemony Software GmbH* running on an *Apple iMac*. Although primarily used in the recording industry for pitch correction, this application was chosen for its ability to decompose chords into their constituent notes and display the frequency and variation in cents for each note.

Figure 4 shows the second and last chords of *Test Piece*. These two chords have been analyzed and displayed in *Melodyne*, as shown in Figure 5, along with a note $E \flat_5$ given by the conductor on a pitch pipe. This was given as it is the first note sung. It may be seen that the note produced by the pitch pipe, which is highlighted, is shown in the top left-hand side of the window. It has the pitch $D\sharp_5$ (i.e. $E \flat_5$) and is 11 cents sharp. (Note that *Melodyne* uses equal temperament, so assumes D sharp is the same note as E flat.)



Figure 4 A fragment of *Test Piece* showing first and last chords

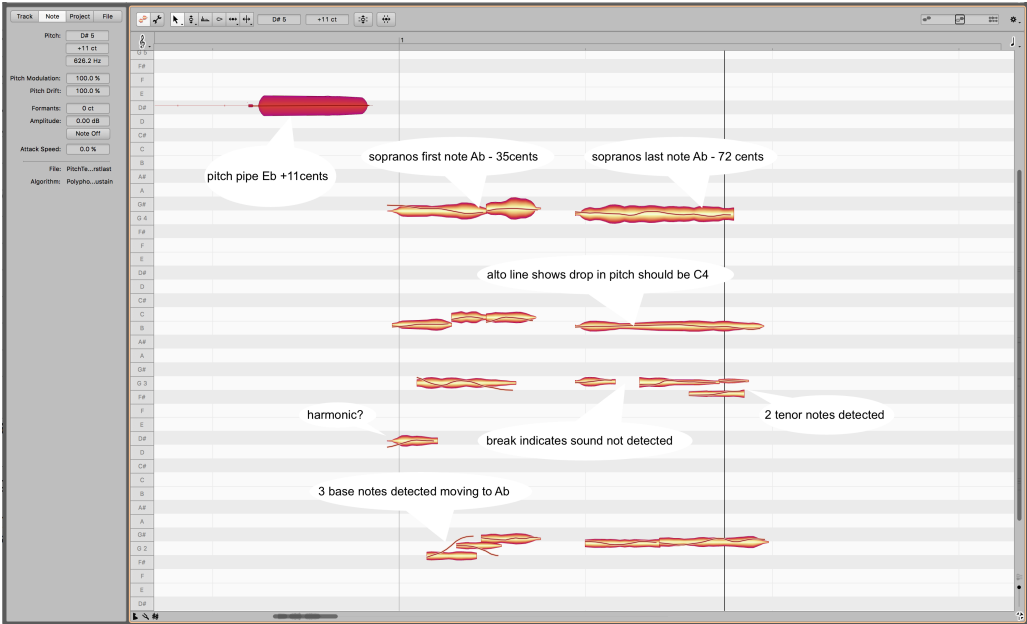


Figure 5 Melodyne window with annotations

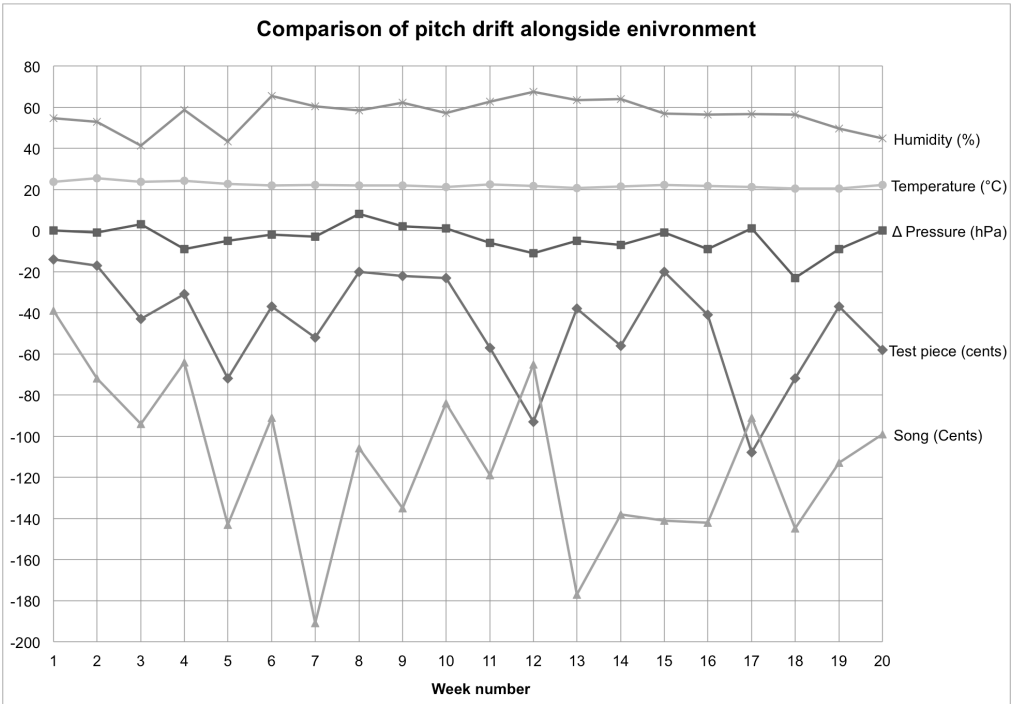


Figure 6 Comparison of pitch drift. For *Test Piece* the pitch difference in cents is between the 2nd and last notes, whereas in the song the difference is between the 1st and last notes.

An analysis of the pitch drift in cents between the sopranos' second and last notes of *Test Piece* (the note pitch is $A \flat_5$) and between their first and last notes of the second song (the note pitch is $E \flat_5$) is shown in Figure 6. The temperature, humidity and change in pressure during the experiment (calculated using the measured value minus starting pressure, in this case 1020hPa) are also shown.

It can be seen clearly from Figure 6 that pitch drift certainly exists over the course of a rehearsal and is much worse some weeks than others. Variation in drift goes from around 20 cents in some weeks to 200 cents (whole tones) in others. It also appears that the second song causes a greater shift than *Test Piece*. Unfortunately, in this single sample there is insufficient evidence to establish whether drift and the environmental conditions are correlated. However, there are some interesting aspects especially at weeks 7, 12 and 17. Week 7 drifted flat by nearly a tone. In weeks 12 and 17 the drift was far greater in *Test Piece* than the song. This is where inspection of the attendance data and the conductor's notes will be useful in researching reasons.

4.2 Pitch Discrimination listening test

At the time of writing, 135 singers have taken part in the listening test giving an overall response rate of 46%. The breakdown by vocal parts is shown in Table 3. Whilst taken across all choirs this number is sufficient for the results to be significant, singers are still being encouraged to take part, even where their pitch drift experiments have come to an end, as the response from some choirs has been disappointing.

Part in Choir	Number
Sopranos	40
Altos	38
Tenors	24
Basses	26
Not stated*	7

Table 3 Numbers of listening test participants by parts (* note that this was optional)

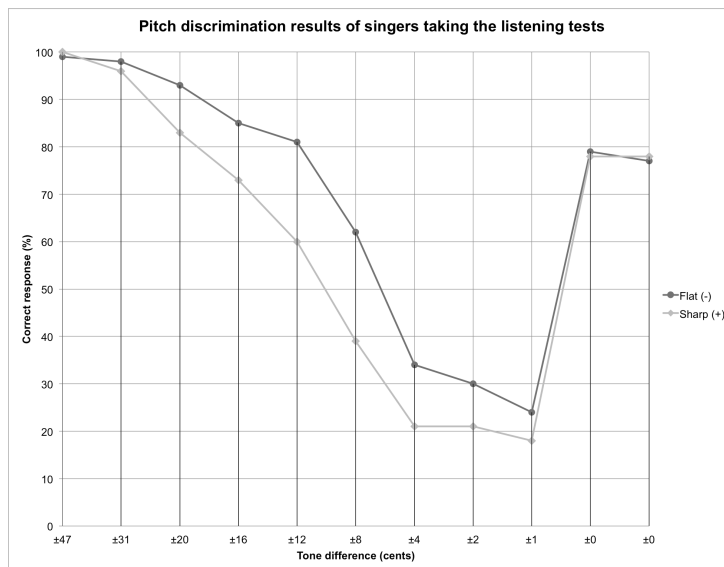


Figure 7 Listening test results comparing discrimination of sharp and flat tones. Note that the two ± 0 points represent the four listening tests where the tones were equal.

The collective response for all singers is shown in Figure 7. It should be noted that the higher the value on the vertical scale, the greater the number of correct responses. Surprisingly, the

response is asymmetric with 62% of singers able to recognize a difference when the second tone is flattened by 8 cents but only 39% recognizing a difference when it is sharpened by 8 cents. The correct response at 1 and 2 cents sharp is only 20%, although this rises to 30% for 1 and 2 cents flat. Further, there is only an 80% correct response when the tones are equal. A possible reason for this may be that many singers are unable to hear a change in tones as the difference becomes small and so make a guess as they *expect* there to be a difference even though they are told in the instructions that an unspecified number of tones are the same. Further investigation into this asymmetry is beyond the scope of this project but these results will still inform the outcomes of the project.

4.3 Rehearsal Venues

A range of building types are used by the participating choirs as shown in Table 4. The venue tends to be determined by the size of the choir and the type of music sung. For example, barbershop choirs use large halls because they involve choreography within their performance. However, for many smaller chamber choirs a room with sufficient chairs will do!

Choir	Venue	Volume	RT ₆₀ (s)	C ₈₀ (dB)
A	Meeting room	175	0.407	16.4
B	Meeting room	322	0.606	8.8
C	Church	4900	1.902	-1.2
D	Church hall	2500*	1.61	0.5
E	Meeting room	225	1.138	8.2
F	Meeting room	168	0.944	5.0
G	Meeting room **	500	0.923	2.9
H	Church	3500	1.71	-0.7
I	Church hall	1000*	1.138	4.4
J	Church	1700	1.429	-1.4
K	School hall	780	1.252	2.8

Table 4 Choir rehearsal venue data (* estimated from RT₆₀) (** formerly a church)

Rindel¹⁴ states that rehearsal rooms used by chamber choirs of 20–30 singers should ideally have a reverberation time of between 1.0s and 1.7s with a volume of 300m³ to 1500m³. Ternström and Sundberg¹⁵ conclude that, whilst individual room characteristics have only a small effect on intonation, a combination of favourable or unfavourable characteristics could have a substantial effect on the performance of the choir, particularly if the singers are amateurs. Ternström¹⁶ found that reflections and reverberations as well as direct sound assisted singers to hear others in the choir. Tonkinson¹⁷ measured the ability of singers to resist singing too loud due to the Lombard effect whereby the voice level is raised in sympathy with the background noise.

The venues for the participating choirs can be split into two distinct categories: rooms under 500m³ and halls and churches above 500m³. One slight anomaly is choir G who rehearse in a deconsecrated small church which is now used as a meeting room. As would be expected, the rooms are less reverberant than the halls and churches, with an RT₆₀ time of under one second. Their clarity values (C₈₀) are mostly above 5dB making them more suitable for speech than music. Choirs rehearsing in such rooms may experience difficulty in hearing others which may make tuning more of a problem. The placing of singers can lead to difficulties with one part hearing another. Anecdotal evidence suggests that choirs who place singers of different parts together have a better sound. It is yet to be seen whether choirs rehearsing in halls and churches experience less pitch drift and likewise if higher sound levels in smaller spaces affect pitch due to the Lombard effect.

5 CONCLUSION

Pitch drift in a *cappella* singing exists and it has been shown to vary from week to week. Furthermore, the drift is flattened and this is despite the singers who responded to the survey being able to recognise smaller differences in pitch when the tone was flattened rather than sharpened. To date, insufficient data has been analyzed to show what may, and indeed may not, cause pitch drift to occur. The acoustic data has yet to be compared with the recordings to see if a more reverberant space helps or hinders singers in maintaining pitch. Each choir has been asked for a register of attendance, since few choirs have the same singers attending each week. This change in ensemble is another variable which, along with the environmental data and the conductors' reports, will be analyzed to see if there is any correlation between these variables and the proven variable drift in pitch.

And what of the pitfalls in the title of this paper? Generally the experiments have taken more than twenty weeks, due to time taken for choirs to prepare for and take part in concerts and competitions. That apart, the experiments have generally worked out very well. One choir had to move venue, from a beautiful Georgian church to a small hall which took them three months to find, putting their experiments on hold and necessitating a second visit for acoustic tests. The Test Piece and the survey both needed changes for the two barbershop choirs – and there was a minor bug in the survey which took a while to find. Another choir has only made 18 recordings, the conductor fearing there would be no singers in the Autumn if they did not finish now! So to the future, which involves analyzing the remaining recordings and correlating the results with the acoustic, attendance, environmental and listening test data to ascertain whether any patterns may be observed not just as to why pitch drift occurs, but may change week by week.

6 ACKNOWLEDGEMENTS

The research team is grateful to all those choirs who have taken part. They have to remain anonymous for now but this research would not be possible without them. The team also gratefully acknowledges the support to this research by Professor David Howard of Royal Holloway University.

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